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The effects of phonotactic probability and neighborhood density on adults' word learning in noisy conditions

Min Kyung Han (Ewha Womans University, Department of Communication Disorders)

Holly L. Storkel (University of Kansas, Speech-Language-Hearing: Sciences & Disorders)

Jaehoon Lee (Texas Tech University, Institute for Measurement, Methodology, Analysis and Policy)

Casey Cox (University of Kansas, Speech-Language-Hearing: Sciences & Disorders)

Abstract

Purpose: Noisy conditions make auditory processing difficult. This study explores whether noisy conditions impact the effects of phonotactic probability (the likelihood of occurrence of a sound sequence) and neighborhood density (phonological similarity among words) on adults' word learning.

Method: Fifty-eight adults learned nonwords varying in phonotactic probability and neighborhood density in either an unfavorable (0dB Signal-to-Noise Ratio, SNR) or a favorable (+8dB SNR) listening condition. Word learning was assessed in a picture naming task by scoring the proportion of phonemes named correctly.

Results: The unfavorable 0dB SNR condition showed a significant interaction between phonotactic probability and neighborhood density in the absence of main effects. Specifically, adults learned more words when phonotactic probability and neighborhood density were both low or both high. The +8dB SNR condition did not show this interaction. These results were inconsistent with those from a prior adult word learning study under quiet listening conditions that showed main effects of word characteristics.

Conclusion: As the listening condition worsens, adult word learning benefits from a convergence of phonotactic probability and neighborhood density Clinical implications are discussed for potential populations who experience difficulty with auditory perception or processing making them more vulnerable to noise.

Key words: language, adults, noise, memory

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Word learning occurs across the lifespan. In adulthood, word learning is crucial for academic, vocational, and social success because adults need to learn the jargon of different academic topics (e.g., "alpha blockers" and "injunction") as well as the specific terminology of their field (e.g., "semantics" and "mental representations"). Thus, the need to learn words as an adult is universal cutting across multiple populations and settings. Although we know much about how people learn new words, most of this research has been conducted in quiet research settings. In contrast, actual word learning occurs in real world environments that are often marked by background noise. For example, young adults who attend universities are confronted with the need to learn the jargon of different academic topics and fields in university classrooms that do not meet standards for classroom acoustics (American National Standards Institute, 2010; American Speech-Language-Hearing Association, 2005; e.g. Hodgson, 1999). Noisy classroom acoustics at universities (and elsewhere) impair influential aspects of word learning such as memory for spoken lecture and recalling of the detailed context of discourse (Gordon, Daneman, & Schneider, 2009; Ljung, Sörqvist, Kjellberg, & Green, 2009). Also, students report that their learning performance is highly influenced by classroom acoustics (Yang, Becerik-Gerber, & Mino, 2013).

People with a variety of different communicative disorders experience difficulty with auditory perception or auditory processing. These include, for example, adults with (1) hearing aids (Bentler & Chiou, 2006), (2) cochlear implants (Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006; Rubinstein, 2004; Shannon, Fu, Galvin, & Friesen, 2004), (3) intellectual disabilities especially Down syndrome (Meuwese-Jongejeugd et al., 2006), and (4) autism spectrum disorder (O'Connor, 2012). Approximately 55% of high school graduates diagnosed with disabilities pursue post-secondary education such as university or other post-high school training (e.g., vocational/technical schools; Institute of Education Sciences, 2011), placing them in the same noisy environment as students without disabilities. However, students with disabilities may find noisy environments even more challenging. Even if not pursuing classroom-based training, work settings also can entail background noise, which may impact workers who need to acquire skills on the job. In fact, adults with disabilities are more likely to be employed in noisy work settings such as production, transportation, and material moving occupations than adults without disabilities (Bureau of Labor Statistics, 2014). Taken together, there is a clear need to expand word learning theories that have been developed from experiments in quiet environments to reflect the real world conditions where learning occurs. As a first step in this direction, the current research focuses on word learning in noise by adults without disabilities to set the foundation for future clinical research with adults with communication disorders.

What is the impact of noise on language processing? When a listening environment is less than optimal, adults tend to rely more on top-down processing of phonological and lexical representations to predict unknown or obscured information than bottom-up processing of acoustic-phonetic information (Wróblewski, Lewis, Valente, & Stelmachowicz, 2012). Noise distorts or degrades acoustic-phonetic information. Thus, in noisy environments, bottom-up processing of distorted and/or degraded acoustic-phonetic information may require more listening effort than in quiet environments (e.g., Rabbitt, 1968), which is less efficient and renders top-down processing of phonological and lexical information more necessary. Past research in quiet listening conditions shows that phonological and lexical representations are used during language processing. However, the effect of these representations may be more marked or different in noisy environments due to the greater reliance on top-down processing. To validate this hypothesis, we investigate the effect of word characteristics on word learning by adults without hearing loss in noise. In the following sections, we will review word learning theory focusing on form representations, the effect of the representations indexed by specific characteristics of words on word learning, and the effect of noise on word learning.

Phonological and Lexical Representations

Known words stored in long-term memory serve as cues for word learning. Specifically, two form representations, phonological and lexical representations, of known words in long-term memory influence word learning (Gupta & MacWhinney, 1997). Phonological representations of a word consist of individual sounds (e.g., /b/, /æ/, /t/ in the word, "bat"), while lexical representations consist of the whole-word sound sequence (e.g., /b æ t/). According to one theory, when a listener hears a word, the listener breaks down the sound information into phonemes and matches them with what is stored in long-term lexical memory (Studdert-Kennedy, 1974). Then, the listener identifies whether the word is known or novel. If the input has an exact match with existing representations in long-term memory, the listener identifies the word as a known word, initiating word retrieval. On the other hand, if the input does not have an exact match with existing lexical representations in long-term memory, the listener identifies the word as novel, initiating word learning. This process of initiating word learning is referred to as *triggering* (e.g., Storkel, Armbrüster, & Hogan, 2006). Note, it is assumed that the individual sounds and sound sequences in a novel word have a matching phonological representation, indicating that the sounds are known sounds rather than novel sounds as in, for example, foreign language learning where the listener may encounter novel sounds. Once triggering of word learning takes place, the sound sequence of the novel word is held in working memory over a short period of time (Baddeley, Gathercole, & Papagno, 1998 for review) with a potential aid of existing phonological and lexical representations while the new lexical representation is being created (e.g., Gathercole, Frankish, Pickering, & Peaker, 1999; Roodenrys & Hinton, 2002; Roodenrys, Hulme, Lethbridge, Hinton, & Nimmo, 2002;Thomson, Richardson, & Goswami, 2005). This process of creating a new lexical representation is often referred to as *configuration* (Leach & Samuel, 2007) or *encoding* (McGregor, 2014).

These two stages of word learning (triggering and configuration) have been distinguished in prior word learning studies by examining how word learning (1) unfolds over time (e.g., Storkel & Lee, 2011), (2) changes across partially versus fully correct responses (e.g., Storkel, Armbrüster, & Hogan, 2006), or (3) differs in distinct tasks (e.g., Pittman & Schuett, 2013). Specifically, in Storkel and Lee (2011), novel words were exposed multiple times at the maximum of six training-testing cycles over two days. Word learning following few exposures was assumed to tap triggering, whereas word learning following many exposures was assumed to tap configuration. In Storkel and colleagues (2006), a partially correct response (i.e., a response was considered as correct only when two out of three phonemes in a word were correct) was assumed to index an early stage of word learning (triggering), whereas a completely correct response (i.e., a response was considered as correct only when three out of three phonemes in a word were correct) was assumed to index a later stage of word learning (configuration). In Pittman and Schuett (2013), the triggering process was measured using a nonword detection task in which children with hearing loss were asked to count the number of nonwords in a presented sentence.

Phonotactic Probability and Neighborhood Density

The role of existing phonological and lexical representations in long-term memory in word learning can be inferred by examining the effects of specific characteristics of words, such as phonotactic probability and neighborhood density. Phonotactic probability, a characteristic of phonological representations (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997), refers to the likelihood of the occurrence of individual sounds and sound sequences in a language. Some individual sounds and sound sequences in a language occur frequently, which are referred to as high probability sequences (e.g., *pass* or *car*), whereas other sounds and sound sequences in a language occur infrequently, which are referred to as low probability sequences (e.g., *wave* or *lose*). Note that phonotactic probability is based on sound sequences in a word, whereas word frequency is based on a whole word. Some high-frequency words consist of sound sequences with high phonotactic probability (e.g., *car*) and other high-frequency words consist of sound sequences with low phonotactic probability (e.g., *book*); some low-frequency words consist of sound sequences with high phonotactic probability (e.g., *kite*) and other low-frequency words consist of sound sequences with low phonotactic probability (e.g., *wave*). On the other hand, neighborhood density, a characteristic of lexical representations (Luce & Pisoni, 1998), refers to the number of known words that sound similar to a given word based on a one sound substitution, deletion, or addition in any word position. For example, neighbors of 'rail' /rel/ include 'gale' /gel/, 'roll' /rol/, 'race' /res/, 'ray' /re/, and 'trail' /trel/. Words with many neighbors are referred to as words with high density (e.g., *rail* or *light*), whereas words with few neighbors are referred to as words with low density (e.g., *house* or *mesh*). An adult word learning study conducted by Storkel, Armbrüster, and Hogan (2006) reveals that adults use these word characteristics in learning novel words under quiet listening conditions.

In Storkel and colleagues (2006), the effects of phonological and lexical characteristics on word learning in adults were strong. In particular, each variable showed an independent effect on word learning without any significant interaction. Specifically, adults learned more words with low phonotactic probability sound sequences than words with high phonotactic probability sound sequences when learning was measured via partially correct responses, which was assumed to index triggering. Words with low phonotactic probability are presumably more easily recognized as new words, triggering word learning efficiently (Storkel, 2009; Storkel et al., 2006; Storkel & Lee, 2011) because they sound less like other known words, whereas words with high phonotactic probability sound very similar to known words (Frisch, Large, & Pisoni, 2000; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). That is, a new word may be mistaken for a known word when phonotactic probability is high, failing to trigger learning of the new word. Regarding the lexical characteristic, adults learned words with high density more accurately than words with low density when learning was measured via fully correct responses, which was assumed to index configuration. Sound sequences in words with high density are hypothesized to be easier to hold in working memory than those with low density because of the support from the many existing lexical representations in long-term memory. This leads to the creation of a more accurate and detailed new lexical representation in long-term memory for high than for low density novel words (Storkel et al., 2006; Storkel & Lee, 2011). These findings present robust evidence that the effects of phonotactic probability and lexical density on word learning are independent.

Effect of Noise on Word Learning

The current model of word learning, however, makes no predictions about the effect of the perceptual environment, such as the impact of background noise on word learning. Listeners are surrounded by noise, and noise degrades acoustic-phonetic input. For the most part, studies of phonotactic probability and neighborhood density have not reflected these real-world conditions, limiting the ecological validity of past findings. Moreover, challenging listening conditions that occur in the real world may hinder lexical retrieval and tax working memory (Heinrich, Schneider, & Craik, 2008; Pichora-Fuller, Schneider, & Daneman, 1995; Rabbitt, 1968), altering the effects of phonotactic probability and neighborhood density on word learning, even for experienced learners (i.e., adults).

Adults generally perform poorly on spoken word recognition in a noisy environment compared to a quiet environment (e.g., Studebaker, Sherbecoe, McDaniel, & Gwaltney, 1999). The interference of noise with word recognition may have a significant influence on a listener's identification of an input word as novel or not, resulting in problems in triggering word learning. Moreover, to segregate the two auditory streams from one another (i.e., speech vs. noise;

Bregman, 1990) in a noisy environment, the central executive in the working memory system may not have enough resources to retain a newly heard phonological form within working memory while a new lexical representation is created in long-term memory (e.g., Barrouillet, Bernardin, & Camos, 2004; Rönnberg, Rudner, Foo, & Lunner, 2008). Consequently, noise may influence the configuration process of word learning. In addition, the effect of neighborhood density may vary across different levels of noise. Taler, Aaron, Steinmetz, and Pisoni, (2010) found that the neighborhood density effect on recognition was larger in a challenging listening condition (-3 dB SNR) than in a favorable listening condition (+10 dB SNR). This result implies that noise may amplify the effect of neighborhood density because adults show greater reliance on top-down processing when the listening condition worsens.

The current study investigated how young adults learn words in background noise with a focus on the effects of phonotactic probability and neighborhood density. The primary question is whether noise modifies the effects of phonotactic probability and neighborhood density on word learning in adults in comparison of the findings of Storkel and colleagues (2006) in quiet listening conditions. To investigate this question, the phonotactic probability and neighborhood density of nonwords-to-be-learned were manipulated. These nonwords then were paired with novel objects, embedded in stories, and trained in two noise conditions (+8 dB SNR vs. 0 dB SNR). These SNRs are commonly observed in college classrooms (e.g., Hodgson, Rempel, & Kenneday, 1999) and served as a favorable (+8 dB SNR) and an unfavorable listening condition (0 dB SNR) for this study. Importantly, this study controlled the confusability of the stimuli so that phonotactic probability and density were not confounded with confusability. Learning was measured via a picture-naming task.

Methods

Participants

Fifty-eight young adults (mean age = 19 years, *SD* = 1.12, range = 18 - 24 years) participated in this study. The participants were all native speakers of American English from the University of Kansas and received partial course credit for participating in the study. All participants self-reported no problems with speech, language, hearing, physical, and medical development. The participants were randomly assigned to one of two Signal-to-Noise Ratio (SNR) conditions: +8 dB SNR and 0 dB SNR.

Materials

The current study utilized the same materials as Storkel et al. (2006) in which the nonword stimuli consisted of 16 consonant-vowel-consonant (CVC) nonwords that were selected to vary in phonotactic probability and neighborhood density. Both characteristics were computed based on the electronic version of *Webster's Seventh New Collegiate Dictionary* (1967).

Phonotactic probability

Positional segment and biphone sums were utilized to measure phonotactic probability. Positional segment sum is computed by summing the positional segment frequencies for each phoneme in a word. Positional segment frequency is how often a target sound in a target word position occurs in a language. Positional segment frequency was computed by adding the log frequency of each word in the dictionary that contained the target sound in the target word position (e.g., /b/ in the initial position in the target word /b æ t/) and dividing by the sum of the log frequency of every word in the dictionary that contained any sound in the target word position (e.g., initial word position) (Storkel, 2004b). Biphone sum is computed by summing the biphone frequencies for each pair of adjacent phonemes in a word. Biphone frequency is how often each adjacent pair of sounds in a target word position occurs in a language. Biphone frequency was computed by adding the log frequency of each word in the dictionary that contained the target pair of sounds in the target word position (e.g., /b æ / in the initial word position in the target word /b æ t/) and then dividing by the sum of the log frequency of every word in the dictionary that contained any sound in the target word position (e.g., initial word position) (Storkel, 2004b). Nonwords were characterized as high or low probability based on a median split. Values above the median were categorized as high, and values at or below the median were categorized as low.

Neighborhood density

The number of real words that differed from each nonword by a single phoneme substitution, addition, or deletion was counted to determine the neighborhood density. As with phonotactic probability, the median value was used for categorizing nonwords as having high or low neighborhood density. Values above the median were categorized as high, and values at or below the median were categorized as low.

The sixteen nonwords in Storkel and colleagues (2006) were equally divided into each of the four following categories: (1) high probability/high density; (2) high probability/low density; (3) low probability/high density; and (4) low probability/low density. Table 1 presents means, ranges, and standard deviations, respectively, of positional and biphone sums, and neighborhood density for each category of the selected nonwords.

Novel object referents

Sixteen pictures of novel objects were selected as referents of the nonwords. This study used the same novel object referents used in Hoover, Storkel, and Hogan (2010), Storkel (2004a), and Storkel and colleagues (2006). Some of these novel objects were adapted from children's stories, and others were created. No novel objects corresponded to objects in the real world. In support of this, children or adults who participated in the past studies were not able to name the objects with a single word. The 16 novel object referents came from four semantic categories: Candy machine, toy, horn, and pet. Each semantic category consisted of four novel object referents, each of which was paired with a nonword from one of the four phonotactic probability/neighborhood density conditions. Table 2 presents examples of the pairing of nonwords with referents.

Stories

The current study used the same two stories from Storkel and colleagues (2006)'s study with the same script and number of presentations for each story. The participants listened to two distinct stories containing eight nonwords each with semantic category balanced across stories. Thus, each story contained two candy machines, two toys, two horns, and two pets. Likewise, each story was balanced in phonotactic probability and neighborhood density. That is, each story contained two high probability/high density nonwords, two high probability/low density nonwords, two low probability/high density nonwords, and two low probability/low density nonwords. There were four versions of each of the two stories to present counterbalanced pairings of nonwords and novel objects across participants.

Each story consisted of three distinct episodes. Each episode contained six visual scenes and corresponding auditory narrative. The first visual scene and corresponding auditory narrative of each episode were an introduction to two main characters and one main activity (e.g., boy and girl characters playing hide and seek with objects). The four succeeding intermediate scenes and auditory narrative provided exposure to the eight nonword-novel object referent pairs. In each intermediate scene, two nonwords in the same semantic category (e.g., horn) were presented. For example, in one of the intermediate scenes, the low probability/high density nonword /hif/ paired with a red s-shaped horn was presented along with the high probability/low density nonword /jɪb/ paired with a yellow looped horn. The order of presentation of the intermediate scenes in each episode was randomized across participants. Following the four intermediate scenes, the last scene and corresponding auditory narrative were a conclusion of the main activity. The same main characters and nonword-novel object pairs appeared in all three episodes in a story, but the main activity changed in each episode. In addition, the number of presentations of the nonword-novel object pairs differed across episodes: in Episode 1, each nonword-novel object pair was presented one time (e.g., "I'll get *paɪb*,"), whereas in Episodes 2 and 3, each pair was presented three times (e.g., "I'll hide *paɪb*. Don't make any noise *paɪb*. I bet you won't be able to find *paɪb*."). Thus, each pair was exposed cumulatively one time after Episode 1, four times after Episode 2, and seven times after Episode 3.

This study used the same auditory recordings created by Storkel and colleagues (2006). The speaking rate used in the recording of the stories, as measured in syllables per second, was not significantly different across the phonotactic probability/neighborhood density conditions. Two judges listened to the recorded stimuli in a quiet condition and transcribed each stimulus to verify recording quality.

Signal-to-Noise Ratios

The nonword stimuli and audio narrative scripts were recorded, digitized, and edited, without any noise added in Storkel and colleagues (2006). For this study, the stimuli and audio narrative scripts from Storkel and colleagues were digitally mixed with broadband white noise at +8 and 0 dB SNR using Matlab® to mimic a classroom noise condition. To generate +8dB and 0dB SNRs, the speech signal was constant at 65dB SPL and the noise was scaled for each SNR. For +8dB SNR, the speech signal was constant at 65dB SPL and the noise was scaled to 57dB SPL (i.e., 8 dB below the speech signal), resulting in a speech signal that is 1.7 ($2^{0.8}$) times louder than the noise. For 0 dB SNR, both speech signal and noise were at 65dB SPL, resulting in the same loudness in the speech signal and the noise. Among these two SNRs, the SNR of +8 dB is one of the commonly reported classroom SNRs (e.g., Hodgson et al., 1999) and served as a favorable listening condition for this study. The SNR of 0 dB is also one of the commonly reported classroom SNRs (e.g., Hodgson et al., 1999) and served as an unfavorable listening condition for this study. The overall intensity of the stimulus files was equalized using Matlab® to yield an intensity level of 65 dB SPL.

Consonant confusion

When noise masks acoustic features of speech sounds, the listener may confuse them with other similar speech sounds (Phatak & Allen, 2007), which can reduce the recognition of a consonant, but also perceptually transform the target consonant into another consonant (Phatak, Lovitt, & Allen, 2008). To examine consonant confusion for the nonwords used in this study, the consonant matrix from Wang and Bilger (1973) was consulted. Wang and Bilger's (1973) consonant matrix was obtained at six SNRs (i.e., -10, -5, 0, +5, +10, and +15 dB SNR) using white noise for 24 CV and 24 VC syllables in which 16 consonants and three vowels were combined. Although Wang and Bilger's (1973) consonant matrix is based on consonant confusions added across all SNRs for each syllable instead of consonant confusions at a given SNR, this consonant matrix still provides information on how likely it is that a given speech sound will be perceived accurately or confused with another speech sound. The critical issue for this study is that the confusability should be similar across low and high probability/density so that phonotactic probability and density are not confounded with segment confusability.

Based on Wang and Bilger's (1973) consonant matrix, the probability of reporting a consonant heard as that consonant when the consonant was spoken in a given consonant position (i.e., first consonant vs. second consonant in a CVC nonword) was computed (e.g., when the consonant /p/ is presented in the initial position in noise, as in the nonword *pim*, 55% of responses indicate that /p/ was heard). Table 1 presents initial and final consonant confusions for the nonwords used in the current study. Overall, no significant differences in the consonant confusions were found among nonword categories for the initial consonants in the CV biphone [$F(3, 12) = .15$, $p = .93$, $\eta^2_p = .04$] or the final consonants in the VC biphone [$F(3, 12) = 1.81$, $p = .20$, $\eta^2_p = .31$]. Thus, consonant confusability is similar across the conditions of interest.

Measures of learning

Learning was measured using a picture naming task. Participants were shown a picture of a novel object referent on the computer screen and they were asked to name the corresponding nonword. The instructions were provided in a quiet condition (i.e., not in any of the SNR conditions) to ensure that participants understood the task. Responses were audio recorded, phonetically transcribed, and scored on a scale from 0-3 based on the number of phonemes correct. Specifically, a naming attempt was scored as 3 if all three phonemes were produced correctly in the correct word position, 2 if two phonemes were correct, 1 if one phoneme was correct, and 0 if no phonemes were correct. The proportion of phonemes correct served as the dependent variable in this study.

Procedure

The stimuli presentation level of 65 dB SPL was checked using a sound level meter immediately before a session began. The sound level meter was placed where participants were seated. Specifically, participants were seated approximately 15 inches away from the center of the computer screen and at 45-degree angle from the external speakers that were placed on the sides of the computer. Participants' responses were recorded using a head-mounted microphone, a digital tape recorder, and a video recorder. DirectRT software (Jarvis, 2002) controlled the presentation of visual and auditory stimuli. Prior to the presentation of a story, the naming task was administered to obtain baseline performance on the measures of learning for each of the eight nonwords from the first story. Participants were told that they would see pictures of objects on the computer screen that they had never seen before and that they would be asked to guess the names of the pictures. A picture of each novel object referent was presented one by one. Following the baseline, the first episode of the first story was presented in the assigned SNR condition. Following this episode, the picture naming task was administered to measure learning of the nonword-novel object referent pairs. This sequence of story episode presentation followed by picture naming was repeated for the second and third episodes of the first story. Then, the second story, which provided training for the remaining eight nonwords, was administered following the same procedures.

Reliability

Transcription reliability was computed for 21% of the participants for productions made on the naming task. Inter-judge transcription reliability was 96% (*SD* = 3.62%, range = 90% - 100%). Scoring reliability was computed for 21% of the participants. Inter-judge scoring reliability was 99.4% (*SD* = 1.04%, range = 96.9% - 100%). Procedural reliability was computed for 21% of the participants to check the consistency of administration procedures for story presentation, naming task, and form completion. Inter-judge procedural reliability was 100% for all samples checked.

Results

The primary aim of this study was to examine the effects of phonotactic probability and neighborhood density on word learning in background noise. It is important to recognize that observations were clustered within participants. That is, each participant was taught multiple novel words and the proportion of phonemes correct was measured for each word at each time point. Analyses that ignore such clustering underestimate standard errors of effect parameters, thereby inflating Type I error rate above the typical alpha level (Moerbeek, 2004). Thus, this study employed hierarchical linear modeling (HLM) that can properly handle multiple observations from the same participant. The model included the fixed effects for phonotactic probability (2 levels: high vs. low), neighborhood density (2 levels: high vs. low), exposure (3 levels: 1 vs. 4 vs. 7 times), noise condition (2 levels: 0dB vs. 8dB SNR), and all possible 2-, 3-, and 4-way interactions among these factors. This model also included random effects of participants and semantic categories (i.e., intercept variances) to capture unexplained variability in word learning across participants and semantic categories. Often there is little shrinkage in the predicted value of residual variance when the sample is large. To avoid this, an over-dispersion residual term was also introduced into the model. The model was fitted using SAS PROC GLIMMIX (SAS Institute, 2002–2010) and pseudo-likelihood estimation for discrete data (Wolfinger & O'Connell 1993). For more details about HLM discrete data analysis, refer to Hox (2010), Goldstein (2003), and Raudenbush and Bryk (2002).

The mean and standard deviation for proportion of correct phonemes across noise conditions are presented in Appendix 1. The model results are presented in Table 3. In terms of the random effects, the predicted correct response rates did not differ across semantic categories (z = 1.10, p = .22) but significantly varied among participants (z = 4.39, p < .001). This suggests that learning was relatively equivalent across semantic categories but differed across individuals, with some participants learning more words than others when all other conditions were equal. In terms of the fixed effects, exposure was significant (p < .001). The correct response rate increased by 3.24 times (OR = 3.24, p < .001) with three more exposures to a target word (from 1 to 4 exposures), and further by 3.75 times (OR = 3.75, p < .001) with three additional exposures to the same target word (from 4 to 7 exposures). In addition, the 3-way interaction of noise condition x phonotactic probability x neighborhood density was significant (p < .001). To demonstrate this interaction, marginal means of the correct response rate were plotted in Figures 1 and 2, along with error bars representing 95% confidence intervals (CI) of the means.

Figure 1 shows the phonotactic probability effect in the 3-way interaction of noise condition x phonotactic probability x neighborhood density by plotting estimated means from the fitted model. In the unfavorable 0dB SNR condition (left panel), when neighborhood density was high, the correct response rates were significantly higher for high phonotactic probability compared to low phonotactic probability (t = 2.38, p = .02, d = 0.32). When neighborhood density was low, however, the opposite pattern was observed. Here, the correct response rates were significantly higher for low phonotactic probability than for high phonotactic probability (t = 2.17, p = .03, d = 0.29). In the favorable +8dB SNR group (right panel), the correct response rates did not differ between high and low phonotactic probability regardless of the level of neighborhood density (*t* = 1.03, *p* = .30, *d* = 0.13 at high density; *t* = 0.73, *p* = .46, *d* = 0.09 at low density).

Figure 2 re-displays the data from Figure 1 to better show the neighborhood density effect in the 3-way interaction of noise condition x phonotactic probability x neighborhood density. In the unfavorable 0 dB SNR condition (left panel), when phonotactic probability was high, the correct response rates were significantly higher for high density compared to low density (*t* = 2.09, *p* = .04, *d* = 0.28). In contrast, when phonotactic probability was low, the opposite pattern was observed. That is, the correct response rates were significantly higher for low density than for high density (*t* = 2.47, *p* = .01, *d* = 0.33). In the favorable 8 dB SNR condition (right panel), the correct response rates were not different between high and low density regardless of the level of phonotactic probability (*t* = 0.46, *p* = .64, *d* = 0.06 at high probability; *t* = 0.76, *p* = .45, *d* = 0.10 at low probability).

To investigate the magnitude of the effect of word characteristics across listening conditions and to compare to the prior study by Storkel and colleagues (2006), the effect size of the interaction between phonotactic probability and neighborhood density was compared among the three listening conditions (i.e., quiet from Storkel et al., 2006, +8 dB SNR, and 0 dB SNR conditions) in reference to Cohen (1988). As seen in Table 4, as the listening condition worsened (i.e., from the quiet condition to +8 dB SNR and to 0 dB SNR), the effect size of the interaction increased. Specifically, the quiet condition in Storkel et al.'s (2006) study showed a negligible effect of the interaction (η_p^2 = .006) when two out of three phonemes and three out of three phonemes were counted as correct, indicating very low practical significance. Note that among the scoring methods used in their study, this scoring method was the closest method to the one used in the current study. The favorable +8 dB SNR condition in the current study showed a small effect of the interaction (*d* = .06 - .13), indicating low practical significance. The unfavorable 0 dB SNR condition in the current study showed a medium effect of the interaction (*d* = .28 - .33), indicating moderate practical significance.

Discussion

The current study was designed to explore whether noise alters the effects of phonotactic probability and neighborhood density on word learning in young adults. The results show a significant main effect of exposure to the target words, which is not a surprising result because learning typically improves as exposure to target words increases (Beck, McKeown, & Kucan, 2002; Nagy, Anderson, & Herman, 1987). More interestingly, the results of the current study indicate a significant interaction between noise, phonotactic probability, and neighborhood density. The interaction between phonotactic probability and neighborhood density was not observed when target words were learned without noise, as seen in Storkel and colleagues (2006). The interaction of phonotactic probability and neighborhood density only emerged at 0 dB SNR where increased word-learning occurred when neighborhood density and phonotactic probability converged. That is, adults showed word-learning advantages for low probability and low density words (i.e., low-low optimal) and for high probability and high density words (i.e., high-high optimal).

The low-low optimal convergence of phonotactic probability and neighborhood density might be explained in terms of the initial triggering process of word learning. Since the study of phonotactic probability involves the frequency of the occurrence of sound sequences in a language, sound sequences that occur less frequently (i.e., those with low phonotactic probability) sound less familiar than sound sequences with high phonotactic probability. Thus, words with low phonotactic probability presumably are more easily recognized as novel words than as known words (Frisch et al., 2000; Vitevitch et al., 1997), which may trigger word learning more efficiently. In complement, since words with low density have fewer neighboring words and therefore less return activation from neighboring words, words with low density have more of a mismatch between the input and the existing lexical representation than words with high density. As with low phonotactic probability, words with low density may be more easily identified as novel, potentially leading to more efficient triggering of word learning. This convergence of low probability and low density for adults in noise mirrors what has been found in preschool children under optimal listening conditions (Hoover et al., 2010). Thus, when word learning is challenging due to lack of word learning experience (i.e., children) or environmental perturbations (i.e., noise), low probability and low density may be optimal for recognizing an input word as novel and efficiently triggering learning.

The high-high optimal convergence of phonotactic probability and neighborhood density might be explained in terms of the later stage of configuration of word learning. When a novel word is encountered, the phonological form of the novel word is held in working memory over a short period of time while also forming a lexical representation of the novel word in long-term memory (Baddeley, 2003). Words with high probability and high density are more likely to be held accurately and/or longer in working memory, due to activation of sound sequences and similar-sounding words in long-term memory (Gathercole et al., 1999; Roodenrys & Hinton 2002; Roodenrys et al., 2002; Thomson et al., 2005). As with the convergence of low probability and low density for adults in noise, this convergence of high probability and high density for adults in noise mirrors what has been found in preschool children under optimal listening conditions (Hoover et al., 2010). Thus, when word learning is challenging due to lack of word learning experience or environmental perturbations, high probability and high density may be optimal for holding recently heard sound sequences in working memory, facilitating the creation of a new representation of the novel word in long-term memory.

With regard to the stages of word learning, the number of exposures could be used to distinguish which stage of word learning, triggering versus configuration, is being tapped, and this approach has been used in studies of child word learning (Hoover et al., 2010). However, the results of the current study reveal no interactions involving exposure, which indicates that these early and later stages may not be discrete in adults in noisy conditions but rather may be overlapping and more integrated. Scoring methods can also be used to distinguish triggering and configuration (Storkel et al 2006). Specifically, Storkel and colleagues (2006) assumed that triggering was indexed when two out of three phonemes in a word were correct, whereas configuration was indexed when three out of three phonemes in a word were correct. Some of the earlier analysis of the current study followed the methods of Storkel and colleagues (2006) but the results did not show a clear differentiation between the two stages, suggesting that the stages may be more integrated in noisy conditions. Therefore, this study used different scoring methods from those in Storkel and colleagues (2006). Specifically, in the current study using hierarchical linear modeling, all possible responses (i.e., zero out of three phonemes, one out of three phonemes, two out of three phonemes, and three out of three phonemes in a word) were analyzed together. Thus, it was not possible to differentiate the effect of a particular variable on a particular response type. Taken together, the inference that low probability/low density facilitates triggering and high probability/high density facilitates configuration warrants further validation. Specifically, future studies that clearly differentiate triggering from configuration by using different tasks to measure each are needed to validate these hypotheses.

In contrast to the unfavorable 0 dB SNR condition, the favorable +8 dB SNR condition did not show a significant interaction between phonotactic probability and neighborhood density. Moreover, significant main effects of phonotactic probability and neighborhood density were not observed. Note that the quiet condition in Storkel and colleagues (2006) revealed only a main effect of phonotactic probability and a main effect of neighborhood density. Thus, along the SNR continuum, the +8 dB SNR condition seems to be a transition point between an ideal listening condition (i.e., quiet) where phonotactic probability and neighborhood density operate independently as cues for word learning and challenging listening conditions (e.g., 0 dB SNR) where a convergence between phonotactic probability and neighborhood density cues is needed.

Interestingly, in terms of the number of words adults learned in a noisy environment, a significant main effect of noise was not observed. That is, adults learned as many words in the unfavorable listening condition (i.e., 0dB SNR) as they did in the favorable listening condition (i.e., +8dB SNR). Due to differences in scoring methods, the current results cannot be directly compared to the prior Storkel and colleagues (2006) results in quiet. The lack of a significant effect of noise in the current study indicates that noise may not influence how many words adults learn but rather the significant interaction indicates that noise influences what types of words adults learn more easily. Viewed in this way, the learning processes (e.g., triggering, configuration) are equally robust across different levels of noise, allowing adults to learn the same number of words. What varies is how existing representations are tapped in the presence of noise. With greater reliance on top-down processing, as would occur in noisy environments, adults may require cue convergence of phonological and lexical representations to make word learning optimal.

The comparison of the effect size of the interaction between phonotactic probability and neighborhood density among the three listening conditions (i.e., quiet from Storkel et al 2006 and +8 dB SNR and 0 dB SNR conditions in the current study) indicates that overall, noise amplified the interaction between phonotactic probability and neighborhood density. Moreover, as the listening condition worsens, a transition may occur from only main effects of phonotactic probability and neighborhood density in the quiet condition to no main effects or interaction in the +8 dB SNR condition to a significant interaction in the 0 dB SNR condition. This pattern suggests that cue convergence is not required to learn words under an ideal listening condition (i.e., quiet condition), but becomes increasingly more important as listening conditions worsen, with a clear need for convergence at 0 dB SNR (and possibly earlier along the SNR continuum).

Taken together, these results suggest that even modest noise levels impact word learning by experienced word learners without hearing loss. More specifically, young adults may need a convergence of cues as listening environment becomes more challenging.

Clinical Implications

The results of the current study suggest that as listening condition worsens, adults may use multiple cues to facilitate word learning compared to a quiet condition. These results imply that clinicians and teachers need to pay attention to what items might be easier to learn depending on the listening conditions and what items likely will require greater training to facilitate word learning. In the following section, we will provide the potential application of these findings to individuals with disabilities such as hearing loss, intellectual disability, and/or autism spectrum disorder who are potentially more vulnerable to noise and likely to be exposed to noisy environments.

In noisy environments, adults with disabilities such as hearing loss, intellectual disability, and autism spectrum disorder may have particular difficulty triggering word learning due to their poorer auditory perception/processing in the presence of environmental noise, leading to poor performance on word recognition in noise. Thus, an interaction between phonotactic probability and neighborhood density during word learning in noise is likely to occur, just as it does for adults without disabilities. Regardless of the magnitude of the interaction, because triggering is likely to be difficult, clinicians and teachers should consider how to call attention to novel words. For example, it may be important to explicitly highlight that a word is new (e.g., "this word may be new for you."). It also may be important to highlight the sound structure by writing the word and writing other contrasting known phonological neighbors. Moreover, discussing similarities and differences between the new word and its known neighbors can further highlight how the new word is unique from other known words and help an adult with or without disabilities successfully trigger word learning.

In terms of configuration in noisy environments, based on studies of working memory, adults with hearing aids may have relatively preserved abilities for configuration due to intact working memory function (cf., Stile, McGregor, & Bentler, 2012, for results from children with hearing aids). In contrast, adults with cochlear implants (e.g., Pisoni & Geers, 2000), adults with intellectual disability (e.g., Schuchardt, Gebhardt, & Mäehler, 2010), and adults with Down syndrome (e.g., Lanfranchi, Cornoldi, & Vianello, 2004) may have difficulties with configuration due to weak working memory function. In cases of working memory difficulties, it is useful to consider how clinicians and teachers can bolster working memory to support the creation of new representations of novel words in long-term memory. The prior suggestions about facilitating triggering likely would have a positive influence on configuration. Use of written language to support spoken language has the potential to reduce the demand on working memory. Moreover, explicitly contrasting the sound sequence of the novel word to known words will likely aid in creating an accurate initial lexical representation in long term memory and help guard against confusion between the new word and other known words.

Conclusion

The current study reveals that adults might benefit from a convergence of word characteristics in a challenging listening condition in which a single word characteristic alone may not provide enough support for word learning. In this study, the optimal conditions in the most challenging listening condition were hypothesized to be low probability - low density for triggering word learning and high probability - high density for creating a new representation in long-term memory. The current study calls attention to the need for better understanding of underlying word learning processes in real world listening environments. Given that noisier conditions alter the effects of phonotactic probability and neighborhood density on word learning by experienced word learners, it would be interesting to explore how noise alters the influence of word characteristics on word learning by less experienced word learners (i.e., children) as well as adults with disabilities who are even more vulnerable to the effect of noise.

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Correspondence concerning this article should be addressed to Min Kyung Han, Ewha Womans University, Department of Communication Disorders, 52 Ewhayeodae-gil, Seodamungu, Seoul, Korea (e-mail: minhan@ewha.ac.kr).

References

American National Standards Institute. (2010). Acoustical performance criteria, design requirements, and guidelines for schools: ANSI S12.60. Acoustical Society of America. doi:10.1121/1.4777003

American Speech-Language-Hearing Association. (2005). Guidelines for addressing acoustics in educational settings [Guidelines]. Available from www.asha.org/policy.

Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders, 36*(3), 189-208. doi:10.1016/S0021-9924(03)00019-4

Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*(1), 158-173. doi: http://dx.doi.org.www2.lib.ku.edu/10.1037/0033-295X.105.1.158

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General, 133*, 83-100. doi:10.1037/0096-3445.133.1.83

Beck, I. L., McKeown, M. G., & Kucan, L. (2002). *Bringing words to life: Robust vocabulary instruction*. New York: The Guilford Press.

Bentler, R. & Chiou, L.-K. (2006). Digital noise reduction: An overview. *Trends in Amplification, 10*, 67-82. doi:10.1177/1084713806289514

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. Cambridge, MA: MIT Press.

Bureau of Labor Statistics, U.S. Department of Labor. (2014). *Persons with a disability: Labor force characteristics – 2014*. Retrieved from http://www.bls.gov/news.release/disabl.nr0.htm

DeBrunhoff, L. (1981). *Babar's anniversary album*. New York: Random House.

Frisch, S. A., Large, N. R., & Pisoni, D. B. (2000). Perception of wordlikeness: Effects of segment probability and length on the processing of nonwords. *Journal of Memory and Language, 42*, 481-496. doi: 10.1006/jmla.1999.2692

Gathercole, S. E., Frankish, C. R., Pickering, S. J., & Peaker, S. (1999). Phonotactic influences on short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*, 84-95. doi:10.1037/0278-7393.25.1.84

Geisel, T. S., & Geisel, A. S. (1958a). *Horton hears a who!* New York: Random House.

Geisel, T. S., & Geisel, A. S. (1958b). *Cat in the hat comes back*. New York: Random House.

Goldstein, H. (2003). Multilevel statistical models (3rd ed.). New York, NY: Oxford University Press.

Gordon, M. S., Daneman, M. & Schneider, B. A. (2009). Comprehension of speeded discourse by younger and older listeners. *Experimental Aging Research, 35*, 277-296. doi:10.1080/03610730902769262

Gupta, P., & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: computational and neural bases. *Brain and Language. Special Issue: Computer models of impaired language, 59*(2), 267-333. doi: 10.1006/brln.1997.1819.

Heinrich, A., Schneider, B. A., & Craik, F. I. (2008). Investigating the influence of continuous babble on auditory short-term memory performance. *The Quarterly Journal of Experimental Psychology, 61*(5), 735-751. doi:10.1080/17470210701402372

Hodgson, M. (1999). Experimental investigation of the acoustical characteristics of university classrooms. *The Journal of the Acoustical Society of America, 106*, 1810-1819. doi: 10.1121/1.427931

Hodgson, M., Rempel, R., & Kenneday, S. (1999). Measurement and prediction of typical speech and background-noise levels in university classrooms during lectures. *The Journal of the Acoustical Society of America, 105*, 226-233. doi: 10.1121/1.424600

Hoover, J. R., Storkel, H. L., & Hogan, T. P. (2010). A cross-sectional comparison of the effects of phonotactic probability and neighborhood density on word learning by preschool children. *Journal of Memory and Language, 63*, 100-116. doi:10.1016/j.jml.2010.02.003

Hox, J. (2010). Multilevel analysis: Techniques and applications (2nd ed.). New York, NY: Routledge.

Institute of Education Sciences, National Center for Special Education Research. (2011). *The post-high school outcomes of young adults with disabilities up to 8 years after high school. A report from the national longitudinal transition study-2 (NLTS2)*. Retrieved from http://ies.ed.gov/ncser/pubs/20113005/pdf/20113005.pdf

Javis, B. G. (2002). DirectRT research software (Version 2002). New York: Empirisoft.

Lanfranchi, S., Cornoldi, C., & Vianello, R. (2004). Verbal and visuospatial working memory deficits in children with Down syndrome. *American Journal on Mental Retardation, 109*, 456-466.

Leach, L., & Samuel, A. G. (2007). Lexical configuration and lexical engagement: When adults learn new words. Cognitive Psychology, 55, 306-353. doi: 10.1016/j.cogpsych.2007.01.001

Ljung, R., Sörqvist,P., Kjellberg, A., & Green, A.-M. (2009). Poor listening conditions impair memory for intelligible lectures: Implications for acoustic classroom Standards. *Building Acoustics, 16,* 257-265. doi:10.1260/135101009789877031

Lorenzi, C., Gilbert, G., Carn, H., Garnier, S., & Moore, B. C. J. (2006). Speech perception problems of the hearing impaired reflect inability to use temporal fine structure. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 103*, 18866-18869. doi: 10.1073/pnas.0607364103.

Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing, 19*, 1-36. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3467695/

McGregor, K. K. (2014). What a difference a day makes: change in memory for newly learned word forms over twenty-four hours. *Journal of Speech, Language, and Hearing Research, 57*, 1842-1850. doi:10.1044/2014_JSLHR-L-13-0273

Meuwese-Jongejeugd, A., Vink, M., van Zanten, B., Verschuure, H., Eichhorn, E., Koopman, D., Bernsen, R., & Evenhuis, H. (2006). Prevalence of hearing loss in 1598 adults with an intellectual disability: Cross-sectional population based study. *International Journal of Audiology*, *45*, 660–669. doi:10.1080/14992020600920812

Moerbeek, M. (2004). The consequence of ignoring a level of nesting in multilevel analysis. *Multivariate Behavioral Research, 39*, 129-149. DOI: 10.1207/s15327906mbr3901_5

Nagy, W. E., Anderson, R. C., & Herman, P. A. (1987). Learning word meanings from context during normal reading. *American Educational Research Journal, 24*, 237-270. Retrieved from http://www.jstor.org.www2.lib.ku.edu/stable/1162893

O'Connor, K. (2012). Auditory processing in autism spectrum disorder: A review. *Neuroscience and Biobehavioral Reviews*, 36, 836–854. doi:10.1016/j.neubiorev.2011.11.008

Phatak, S. A., & Allen, J. B. (2007). Consonant and vowel confusions in speech-weighted noise. *The Journal of the Acoustical Society of America, 121*, 2312-2326. doi:10.1121/1.2642397

Phatak, S. A., Lovitt, A., & Allen, J. B. (2008). Consonant confusions in white noise. *The Journal of the Acoustical Society of America, 124*, 1220-1233. doi:10.1121/1.2913251

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *The Journal of the Acoustical Society of America, 97*, 593-608. doi:10.1121/1.412282

Pisoni, D. D., & Geers, A. E. (2000). Working memory in deaf children with cochlear implants: Correlations between digit span and measures of spoken language processing. *Annals of Otology, Rhinology, & Laryngology, Suppl., 185*, 92-93. Available from http://aor.sagepub.com/

Pittman, A. L., & Schuett, B. C. (2013). Effects of semantic and acoustic context on nonword detection in children with hearing loss. *Ear and Hearing, 34*, 213-220. doi: 10.1097/AUD.0b013e31826e5006.

Rabbitt, P. M. (1968). Channel-capacity, intelligibility and immediate memory. *Quarterly Journal of Experimental Psychology, 20*, 241-248. doi:10.1080/14640746808400158

Raudenbush, S.W., & Bryk, A.S. (2002). Hierarchical linear models (2nd ed.). Thousand Oaks, CA: Sage Publications.

Rönnberg, J., Rudner, M., Foo, C., & Lunner, T. (2008). Cognitin counts: A working memory system for ease of language understanding (ELU). *International Journal of Audiology, 47*, S99-S105. doi:10.1080/14992020802301167

Roodenrys, S., & Hinton, M. (2002). Sublexical or lexical effects on serial recall of nonwords? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 29-33. doi:10.1037//0278-7393.28.1.29

Roodenrys, S., Hulme, C., Lethbridge, A., Hinton, M., & Nimmo, L. M. (2002). Word-frequency and phonological-neighborhood effects on verbal short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 1019-1034. doi:10.1037//0278-7393.28.6.1019

SAS Institute. (2002–2010). *SAS/STAT 9.3 user's guide*. Cary, NC: SAS Institute Inc.

Schuchardt, K., Gebhardt, M., & Mäehler, C. (2010). Working memory functions in children with different degrees of intellectual disability. Journal of Intellectual Disability Research, 54, 346-353. doi: 10.1111/j.1365-2788.2010.01265.x

Shannon, R. V., Fu, Q.-J., Galvin, J., & Friesen, L. (2004). Speech perception with cochlear implants. In F.-G. Zeng, A.N. Popper, R.R. Fay (Eds.), *Cochlear implants: auditory prostheses and electric hearing*, 334-76. New York, NY: Springer.

Stiles, D. J., McGregor, K. K., & Bentler, R. A. (2012). Vocabulary and working memory in children fit with hearing aids. *Journal of Speech, Language, and Hearing Research, 55*, 154-167. doi:10.1044/1092-4388(2011/11-0021)

Storkel, H. L. (2004a). Do children acquire dense neighborhoods? An investigation of similarity neighborhoods in lexical acquisition. *Applied Psycholinguistics, 25*, 201-221. doi:10.1017/S0142716404001109

Storkel, H. L. (2004b). Methods for minimizing the confounding effects of word length in the analysis of phonotactic probability and neighborhood density. *Journal of Speech, Language, and Hearing Research, 47*, 1454-1468. doi:10.1044/1092-4388(2004/108)

Storkel, H. L. (2009). Developmental differences in the effects of phonological, lexical and semantic variables on word learning by infants. *Journal of Child Language, 36*, 291-321. doi:10.1017/S030500090800891X

Storkel, H. L., Armbrüster, J., & Hogan, T. P. (2006). Differentiating phonotactic probability and neighborhood density in adult word learning. *Journal of Speech, Language, and Hearing Research, 49*(6), 1175-1192. doi:10.1044/1092-4388(2006/085)

Storkel, H. L., & Lee, S.-Y. (2011). The independent effects of phonotactic probability and neighbourhood density on lexical acquisition by preschool children. *Language and Cognitive Processes, 26*, 191-211. doi:10.1080/01690961003787609

Studdert-Kennedy, M. (1974). The perception of speech. In T. A. Sebeok (Ed.), *Current Trends in Linguistics* (2349-2385). The Hague, the Netherlands: Mouton.

Studebaker, G. A., Sherbecoe, R. L., McDaniel, D. M., & Gwaltney, C. A. (1999). Monosyllabic word recognition at higher-than-normal speech and noise levels. *Journal of Acoustical Society of America, 105*. doi:10.1121/1.426848

Taler, V., Aaron, G. P., Steinmetz, L. G., & Pisoni, D. B. (2010). Lexical neighborhood density effects on spoken word recognition and production in healthy aging. *The Journals of Gerontology:Series B: Psychological Sciences and Social Sciences, 65*, 551-560. doi:10.1093/geronb/gbq039

Thomson, J. M., Richardson, U., & Goswami, U. (2005). Phonological similarity neighborhoods and children's short-term memory: typical development and dyslexia. *Memory & Cognition, 33*, 1210-1219. doi:10.3758/BF03193223

Vitevitch, M. S., Luce, P. A., Charles-Luce, J., & Kemmerer, D. (1997). Phonotactics and syllable stress: Implications for the processing of spoken nonsense words. *Language & Speech, 40*, 47-62. doi:10.1177/002383099704000103

Wang, M. D., & Bilger, R. C. (1973). Consonant confusions in noise: a study of perceptual features. *The Journal of the Acoustical Society of America, 54*, 1248-1266. doi:10.1121/1.1914417

Webster's seventh new collegiate dictionary. (1967). Los Angeles: Library Reproduction Service.

White, K. R., Forsman, I., Eichwald, J., & Munoz, K. (2010). The evolution of early hearing detection and intervention programs in the United States. *Seminars in Perinatology, 34*, 170-179. doi:10.1053/j.semperi.2009.12.009

Wolfinger, R., & O'Connell, M. (1993). Generalized linear mixed models: A pseudo-likelihood approach. *Journal of Statistical Computation and Simulation, 48*, 233–243. doi: 10.1080/00949659308811554

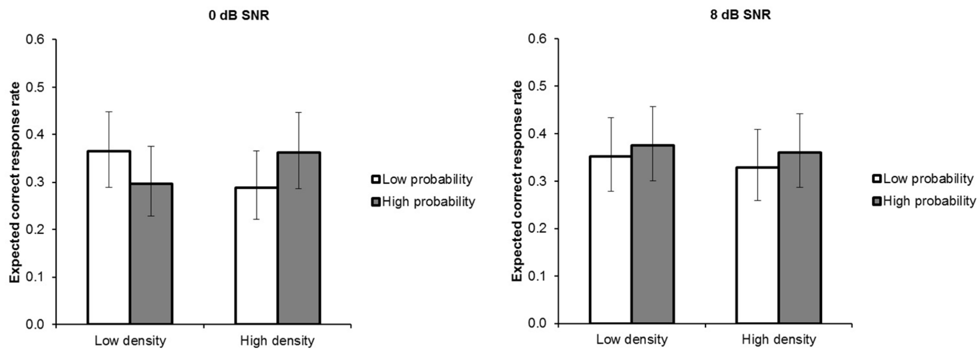
Wróblewski, M., Lewis D. E., Valente D. L., & Stelmachowicz P. G. (2012). Effects of reverberation on speech recognition in stationary and modulated noise by school-aged children and young adults. *Ear and Hearing, 33*, 731-744. doi:10.1097/AUD.0b013e31825aecad

Yang, Z., Becerik-Gerber, B., & Mino, L. (2013). A study on student perceptions of higher education classrooms: Impact of classroom attributes on student satisfaction and performance. *Building and Environment, 70*, 171-188. doi:10.1016/j.buildenv.2013.08.030

Figure Caption

Figure 1. The mean expected correct response rate for low phonotactic probability (open bars) versus high phonotactic probability (shaded bars) for low versus high density by participants in the 0 dB SNR condition (left panel) versus +8 dB SNR group (right panel). Error bars show the 95% confidence interval around the mean.

Figure 2. The mean expected correct response rate for low neighborhood density (open bars) versus high neighborhood density (shaded bars) for low versus high phonotactic probability by participants in the 0 dB SNR condition (left panel) versus +8 dB SNR group (right panel). Error bars show the 95% confidence interval around the mean.



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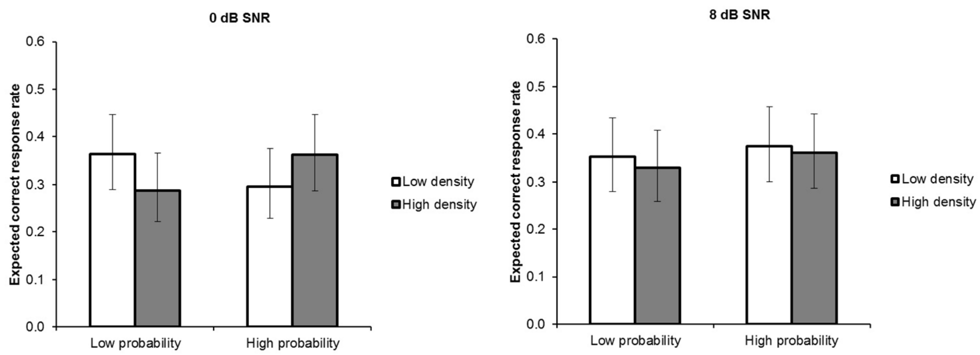

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Table 1

Characteristics of Phonotactic Probability and Neighborhood Density of the Nonword Stimuli with Consonant Confusion

	High phonotactic probability		Low phonotactic probability	
	High density[a]	Low density[b]	High density[c]	Low density[d]
Positional sum				
M	0.16	0.15	0.09	0.09
Range	(0.14-0.18)	(0.12-0.20)	(0.09-0.10)	(0.07-0.10)
SD	0.02	0.03	0.01	0.01
Biphone sum				
M	0.0056	0.0065	0.0017	0.0009
Range	(0.0027-0.0130)	(0.0023-0.0157)	(0.0007-0.0023)	(0.0006-0.0011)
SD	0.0050	0.0063	0.0007	0.0002
Neighborhood density				
M	20	10	17	7
Range	(17-21)	(5-13)	(13-22)	(4-10)
SD	2	3	4	3
Consonant Confusion: Initial Position				
M	60.75	57.75	55.25	58.25
Range	(48-71)	(48-71)	(45-71)	(45-71)
SD	11.09	9.64	11.67	13.65
Consonant Confusion: Final Position				

M	51.25	48.00	56.00	53.25
Range	(47-57)	(43-53)	(52-61)	(48-61)
SD	4.65	5.77	3.92	5.5

Nonwords:

[a] /pim joʊn mɛk wæd/

[b] /hɑn nɛp jɪb paɪb/

[c] /jeɪm feɪg hif naʊt/

[d] /faʊg jʌd wɑf mug/

Table 2

The Examples of Nonword-Novel Object Pairs From Semantic Category Across Form Characteristics

Semantic category	High phonotactic probability		Low phonotactic probability	
	High density	Low density	High density	Low density
Candy machine	Red circle candy[1] *pim*	Blue star candy[1] *han*	Blue triangle candy[1] *jeɪm*	Orange rectangle candy[1] *faʊg*
Toy	Punch toy with spring[2] *joʊn*	Gun toy with string[2] *nɛp*	Flying arrow[2] *feɪg*	Shooting gas[2] *jʌd*
Horn	Red snake horn[2] *mɛk*	Yellow looped horn[2] *jɪb*	Red s-shaped horn[2] *hif*	Blue straight horn[2] *waf*
Pet	Green caterpillar[3] *wæd*	Blue armadillo[4] *paɪb*	Yellow bat[4] *naʊt*	Red elephant[4] *mug*

[1]Storkel, et al. (2006)

[2]Geisel & Geisel (1958a,b)

[3]DeBrunhoff (1981)

[4]Mayer (1992)

Table 3

Generalized Mixed Modeling Results

Fixed effect	Estimate	*SE*	OR	*F*	*num. df*	*den. df*	*p*
Intercept	0.62	0.21					
Noise Condition (C) (ref. = 8)				0.51	1	2701	0.473
0 (C1)	-0.30	0.26	0.74				
Exposure (E) (ref. = 7)				326.72	2	2701	0.000
1 (E1)	-2.50	0.25	0.08				
4 (E2)	-1.18	0.21	0.31				
Density (D) (ref. = Low)				0.59	1	2701	0.442
High (D1)	-0.39	0.21	0.68				
Probability (PP) (ref. = Low)				0.95	1	2701	0.330
High (PP1)	0.00	0.21	1.00				
C × E				0.69	2	2701	0.503
C1, 1	0.47	0.35					
C1, 4	0.58	0.30					
C × D				0.18	1	2701	0.670
C1, D1	0.21	0.29					
C × PP				0.56	1	2701	0.456
C1, PP1	-0.04	0.30					
E × D				1.45	2	2701	0.235
E1, D1	0.17	0.36					
E2, D1	0.69	0.29					
E × PP				0.56	2	2701	0.572
E1, PP1	0.26	0.34					
E2, PP1	0.04	0.30					
D × PP				6.21	1	2701	0.013
D1, PP1	0.33	0.30					
C × E × D				1.17	2	2701	0.310
C1, E1, D1	-0.43	0.51					
C1, E2, D1	-0.94	0.42					
C × E × PP				0.87	2	2701	0.420
C1, E1, PP1	-0.72	0.50					
C1, E2, PP1	-0.38	0.42					
C × D × PP				4.75	1	2701	0.029
C1, D1, PP1	0.02	0.42					
E × D × PP				0.01	2	2701	0.993
E1, D1, PP1	-0.33	0.49					
E2, D1, PP1	-0.51	0.42					
C × E × D × PP				1.53	2	2701	0.217
C1, E1, D1, PP1	0.74	0.72					

C1, E2, D1, PP1	1.01	0.59

Random effect	Estimate	*SE*
Student	0.35	0.08
Semantic	0.04	0.03
Residual	1.70	0.05

SE = standard error, OR = odds ratio, *df* = degrees of freedom.

Table 4

Effect Size of Main Effects of and Interactions Between Phonotactic Probability and Neighborhood Density Across Listening Conditions

	Quiet*	+8 dB SNR	0 dB SNR
Main effect			
PP	$\eta_p^2 = .164$ (large)	*d* = .05 (small)	*d* = .01 (small)
D	$\eta_p^2 = .274$ (large)	*d* = .03 (small)	*d* = .01 (small)
Interaction	$\eta_p^2 = .006$ (small)		
PP at high D		*d* = .13 (small)	*d* = .32 (medium)
PP at low D		*d* = .09 (small)	*d* = .29 (medium)
D at high PP		*d* = .06 (small)	*d* = .28 (medium)
D at low PP		*d* = .10 (small)	*d* = .33 (medium)

Note . PP = Phonotactic probability; D = Neighborhood density.
*: effect size was taken from Storkel et al. (2006) when two out of three and three out of three phonemes were responded correctly. Since the interaction was not significant, the follow-up comparisions were not computed.

Appendix 1. Mean and Standard Deviation for Proportion of Correct Phonemes Across Noise Conditions.

Noise condition	Exposure	Density	Probability	N	M	SD	% of responses with 3 correct phonemes	% of responses with 2 correct phonemes	% of responses with 1 correct phoneme	% of responses with 0 correct phonemes
0	1	High		224	0.13	0.25				
			High	112	0.14	0.26	2.68	8.93	16.07	72.32
			Low	112	0.11	0.24	2.68	6.25	13.39	77.68
		Low		224	0.14	0.27				
			High	112	0.11	0.24	3.57	4.46	12.5	79.46
			Low	112	0.16	0.29	2.68	16.96	7.14	73.21
	4	High		224	0.39	0.36				
			High	112	0.44	0.36	15.18	34.82	17.86	32.14
			Low	112	0.34	0.36	9.82	28.57	15.18	46.43
		Low		224	0.39	0.38				
			High	112	0.35	0.39	18.75	14.29	19.64	47.32
			Low	112	0.43	0.36	12.50	41.07	10.71	35.71
	7	High		224	0.57	0.33				
			High	112	0.60	0.34	26.79	43.75	13.39	16.07
			Low	112	0.53	0.33	16.96	44.64	19.64	18.75
		Low		224	0.57	0.36				
			High	112	0.57	0.37	30.36	28.57	21.43	19.64
			Low	112	0.57	0.36	25.00	44.64	8.04	22.32
8	1	High		240	0.14	0.27				
			High	120	0.15	0.29	5.00	10.83	8.33	75.83
			Low	120	0.12	0.25	1.67	10.83	10.00	77.50
		Low		240	0.16	0.30				
			High	120	0.18	0.31	6.67	11.67	10.83	70.83
			Low	120	0.15	0.29	5.00	10.00	9.17	75.83
	4	High		240	0.43	0.39				
			High	120	0.41	0.39	18.33	26.67	14.17	40.83
			Low	120	0.44	0.38	18.33	32.50	12.50	36.67
		Low		240	0.38	0.40				
			High	120	0.38	0.42	23.33	16.67	11.67	48.33
			Low	120	0.38	0.39	15.00	28.33	10.83	45.83
	7	High		240	0.59	0.39				
			High	120	0.63	0.41	44.17	25.00	5.00	25.83
			Low	120	0.55	0.36	24.17	40.83	11.67	23.33
		Low		240	0.64	0.39				
			High	120	0.64	0.39	45.83	17.50	19.17	17.50
			Low	120	0.64	0.40	44.17	25.00	9.17	21.67